

Multi-Partner Experiment to Test Volcanic-Ash Ingestion by a Jet Engine

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A research team of U.S. Government agencies and engine manufacturers are designing an experiment to test volcanic-ash ingestion by a NASA owned F117 engine that was donated by the U.S. Air Force. The experiment is being conducted under the auspices of NASA's Vehicle Integrated Propulsion Research (VIPR) Program and will take place in early 2014 at Edwards AFB in California as an on-ground, on-wing test. The primary objectives are to determine the effect on the engine of several hours of exposure to low to moderate ash concentrations, currently proposed at 1 and 10 mg/m³ and to evaluate the capability of engine health management technologies for detecting these effects. A natural volcanic ash will be used that is representative of distal ash clouds many 100's to ~1000 km from a volcanic source —i.e., the ash should be composed of fresh glassy particles a few tens of microns in size. The glassy ash particles are expected to soften and become less viscous when exposed to the high temperatures of the combustion chamber, then stick to the nozzle guide vanes of the high-pressure turbine. Numerous observations and measurements of the engine's performance and degradation will be made during the course of the experiment, including borescope and tear-down inspections. While not intended to be sufficient for rigorous certification of engine performance when ash is ingested, the experiment should provide useful information to aircraft manufacturers, airline operators, and military and civil regulators in their efforts to evaluate the range of risks that ash hazards pose to aviation.

Multi-Partner Experiment to Test Volcanic-Ash Ingestion by a Jet Engine

Status Report of Feb. 2013

John Lekki (NASA), Eric Lyall (USAF), Marianne Guffanti (USGS), John Fisher (FAA),
Beth Erlund & Rory Clarkson (Rolls Royce), Allan van de Wall (GE)

Quick Overview:

- The experiment is being undertaken by a research team of U.S. Government agencies (NASA, US Air Force, FAA, USGS) and engine and aircraft equipment manufacturers (Pratt & Whitney, GE, Rolls Royce, Boeing).
- Planned for spring of 2014 at Edwards Air Force Base in southern California using a NASA owned F117 engine. Will be a ground-based, on-wing test.
- Primary test objectives are:
 1. To improve understanding of the effect on the engine of several hours of exposure to low to moderate concentrations of volcanic ash
 2. Determine how well engine degradation from volcanic ash is detected with an expanded engine health management system
- Desired outcome is to provide aircraft manufacturers, airline operators, and military and civil regulators with improved information for evaluating the impact of ash hazards pose on aviation.

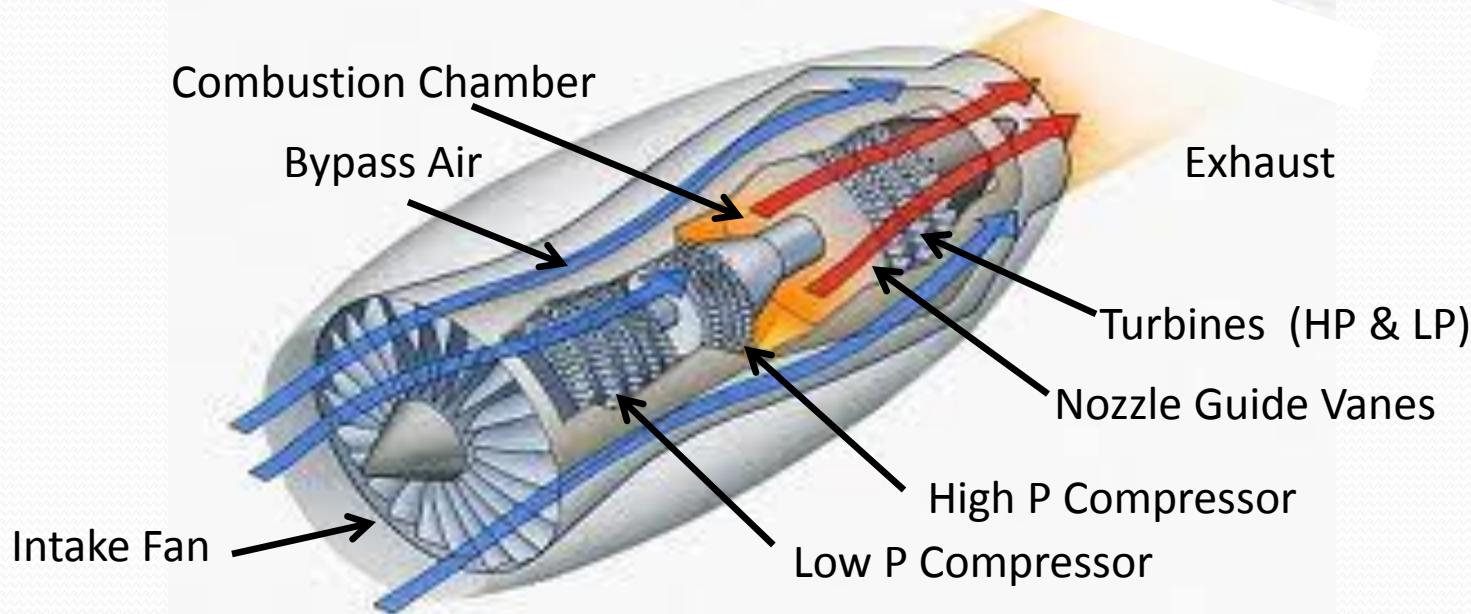
Background:

- Ingestion tests were conducted in the 1980's as outgrowth of nuclear bomb scenarios.
Tests documented severely damaging effects of high concentrations (100's of mg/m³) of "dust" (blends of materials, one component being volcanic ash).
- Now we need to know more about the effect of flying through much lower concentrations, such as those that closed European airspace during the 2010 eruption of Eyjafjallajökull Volcano—i.e., a few mg/m³.
- The current test is being conducted under the auspices of an ongoing NASA program, Vehicle Integrated Propulsion Research (VIPR), which supports development of sensors and models to measure jet-engine performance and diagnose problems during operation. So, VIPR is well-suited to address ash-ingestion testing.
- NASA aeronautical expertise is provided by engineers from Glenn Research Center in Ohio and Dryden Flight Research Center in California.

Background:

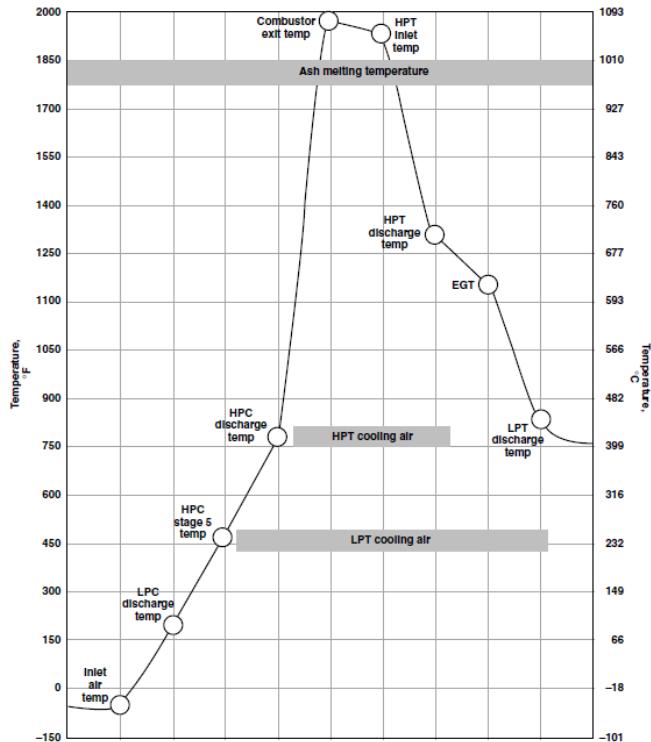
- Major collaborator is the Air Force Research Lab at Wright-Patterson Air Force Base in Ohio. Providing funding and engineering staff.
- FAA also is providing funding. FAA views this as R&D and not sufficient basis for regulations certifying engine performance in ash-contaminated airspace.
- USGS asked to participate to recommend a source of natural ash for the test.
- P&W is providing expertise specific to its engine, GE is building rig to disperse ash into engine, Rolls Royce is funding ash collection and processing.
- All groups participating in test design.

Basics of a Turbofan Jet Engine:



- 1) Air enters through intake fan; some it bypasses the engine core.
- 2) Multiple compressors greatly increase pressure & temperature of air.
- 3) Hot compressed air exits high-pressure compressor into combustion chamber where it is mixed with fuel & burned.
- 4) In turbine stages, thermal energy is converted to mechanical energy. “Nozzle guide vanes” are airfoils that direct the very hot gas stream from combustion onto turbine rotor blades, causing them to rotate & turn a shaft that turns compressors & fan. Voila—the engine cycle continues!

Ash in the Engine:



HPC Delivery: temperature exiting the high-pressure compressor.

TGT/EGT = Turbine Gas Temperature (in the UK) / Exhaust Gas Temperature (in the US): temperature used to judge level of deterioration in an engine.

- Compressors: Drying of ash occurs. Ash particles pulverized. Compressor erosion & abrasion possible.
- Combustion chamber at cruise in engine being tested not quite hot enough to melt all crystals (e.g., 1100-1500 °C for feldspars). But it is hot enough to soften glass (Δ viscosity at ~800°C for rhyolite to ~1000 °C for basalt).
- Exiting gas stream hits *nozzle guide vanes*. Softened glass sticks (cooled slightly but still softened?). Temperature drops through turbines hundred of degrees. Any remaining softened glass moving through cools & re-hardens (to get blown out engine?).

MODERN ENGINES RUN HOTTER THAN TEST ENGINE.

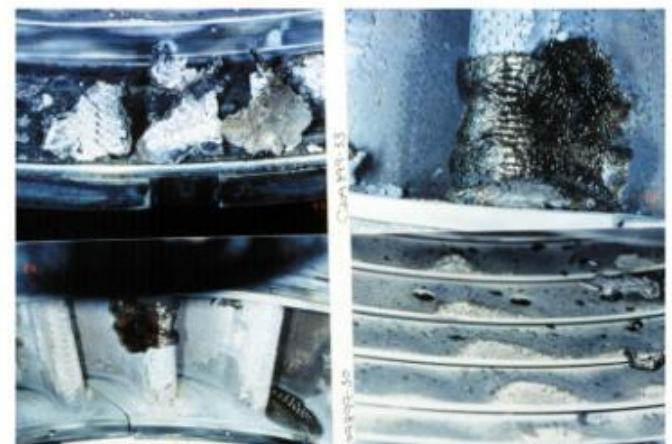
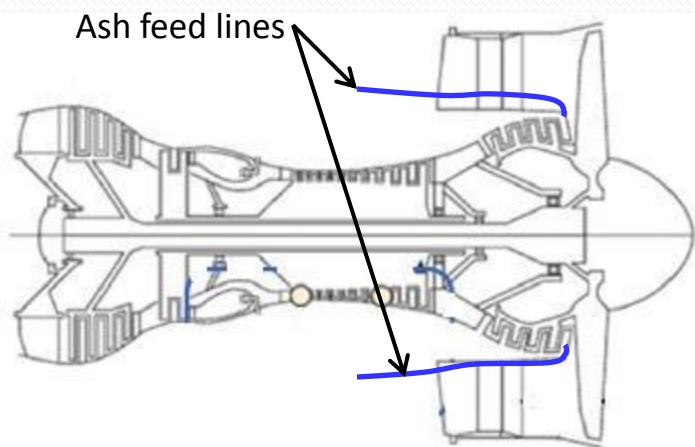
Engine Temperature Data is from: NASA/TM-2003-212030

Ash Concentrations:

- Two ash concentrations around the “visible” threshold will be tested, **currently proposed at 1 and 10 mg/m³.**
 - Depending on conditions, 1 mg/m³ ash cloud may or may not be visible to the human eye. It also represents the approximate lower limit of what reliably can be injected into the engine in a controlled experiment.
 - A 10 mg/m³ ash cloud most likely will be visible and the order of magnitude difference in concentrations is expected to cause discernible differences in engine degradation effects.
- This test range also includes the “safety-case” threshold used on ash concentration charts introduced in Europe in 2010 (2 mg/m³).

Ash Testing Methodology:

- Ash injection – into engine core flow aft of fan (enables ingestion of known quantity of ash)
 - Rig to be tested in summer of 2013
- Preliminary test plan defined
 - Extended exposure to low level concentrations at simulated cruise followed by steady state evaluation of engine behavior
 - Post exposure borescope evaluation
 - Steady state evaluation of engine behavior
 - Team decision required to test at higher concentration levels
 - Final post exposure hardware evaluation
- Expected test results for public release*
 - Normalized impact on engine behavior
 - Hardware damage assessment

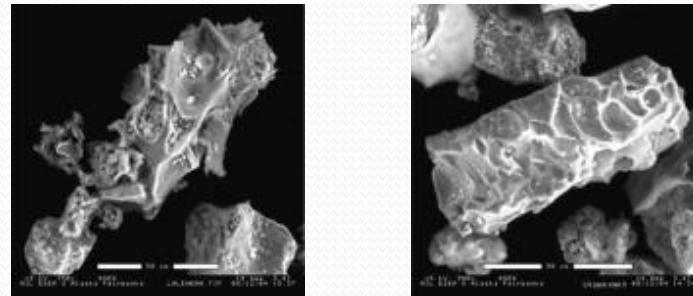


Damage from 1989 severe ash encounter in Alaska

* Proprietary data rights & export control/ITAR (International Traffic in Arms Regulations – US Govt regulations controlling defense related technical data and items) issues are being worked out

Ash Source:

- Ash introduced into engine needs to be representative of distal ash cloud that might be encountered by an aircraft 100's of kilometers from volcano.



- Need to consider:
 - Particle size: Particles in distal clouds are a few tens of microns.
 - Composition: Mostly glass particles, which are more silicic than bulk content of magma (e.g., Redoubt andesite: bulk $\text{SiO}_2=59\%$, glass $\text{SiO}_2=77\%$; Pinatubo dacite: bulk $\text{SiO}_2=64\%$, glass $\text{SiO}_2=70\%$).
 - Freshness: Not a lot of secondary hydration (water that infiltrates glass matrix or crystal structure) because of concern that melting temperature and viscosity may be affected (more on this later).
 - Presence of volcanic gases: Planning team has decided to ignore this variable and focus solely on particulates in cloud.

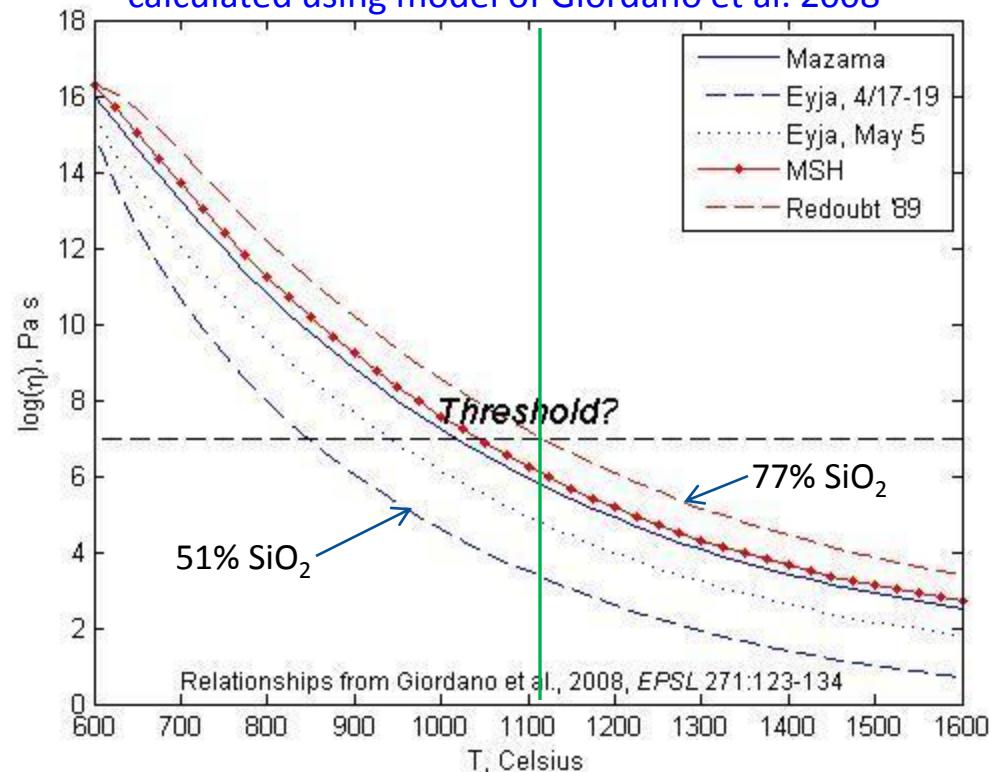
Ash Properties--Viscosity:

- Viscosity of ash is strongly dependent on its SiO_2 content (see graph). But behavior of less viscous compared to more viscous glass in engine is speculative. Is there a “sticking” threshold of viscosity? 10^7 Pa-s has been suggested by Ulli Keuppers of Ludwig Maximilian Univ. in Munich.

For a given temperature, viscosity of basaltic glass is a few orders of magnitude lower than of rhyolitic glass.

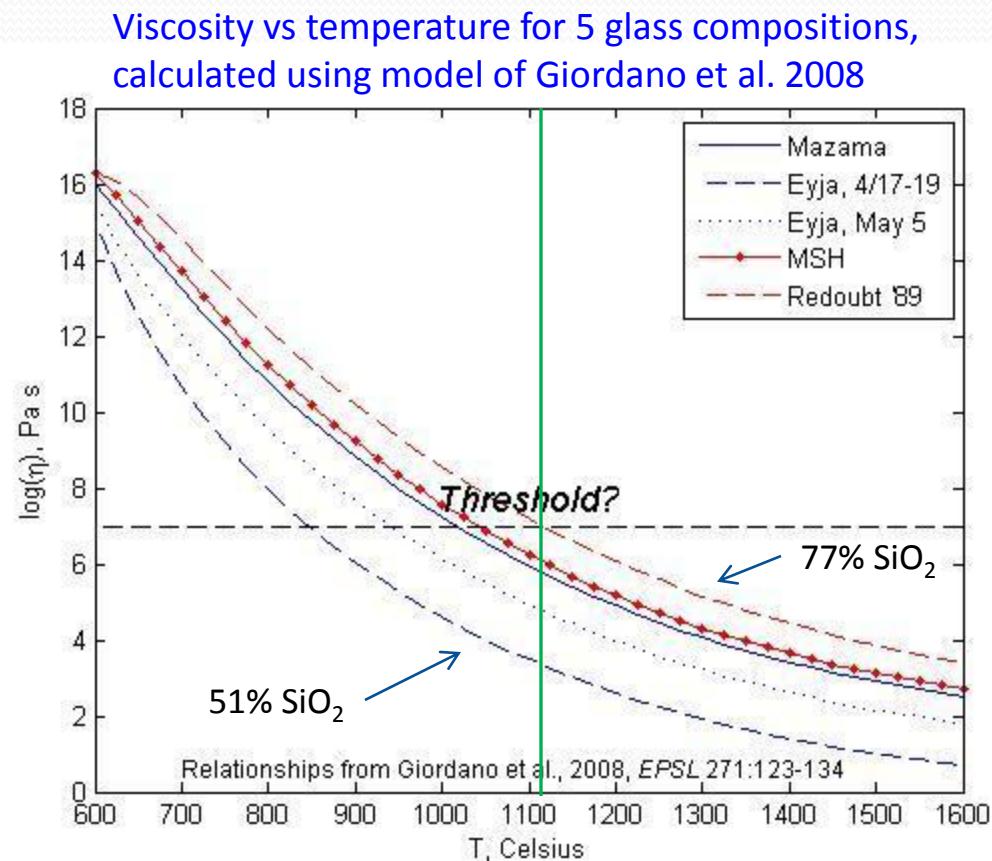
Graphic courtesy of Larry Mastin, USGS

Viscosity vs temperature for 5 glass compositions, calculated using model of Giordano et al. 2008



Ash Properties--Viscosity:

- Green line ($\sim 1100^\circ\text{C}$) is approximate temperature of ash entrained in gas stream from combustor as it hits nozzle guide vanes (in the older test engine).
- Broad range of glass compositions will reach the sticking threshold at that temperature—i.e., material with viscosity of 10^7 Pa sec or less will stick.
- Glass is sticking while hot & softened.



Graphic courtesy of Larry Mastin, USGS

Ash Properties—Role of Calcium:

- Previous ingestion experiments by Dunn used 2 different volcanic materials:
 - (1) blend of sand, clay, bentonite, & Mt. St. Helens ash (25% glass).
 - (2) blend of sand, clay, bentonite, & basaltic scoria (80% glass).

These blends (and others with no volcanic ash) were created to simulate dust cloud created by nuclear blast, then used later used for volcanic project

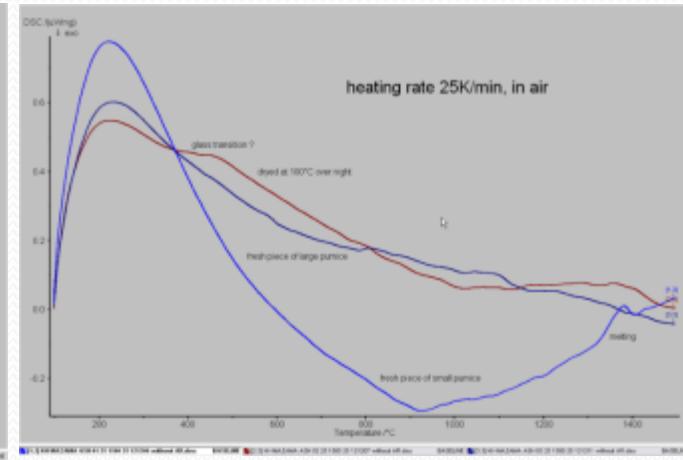
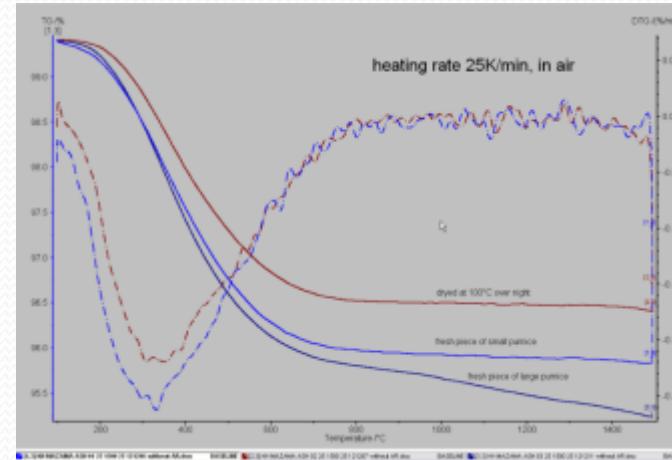
- More deposition of material on turbine occurred with blend 2 than blend 1. Dunn attributed this to higher calcium content of blend 2, extrapolating the behavior of calcite (CaCo_3) in other *no-ash* blends.
- Basalt does have more calcium than silicic rocks like Mt. St. Helens dacite. But calcium is not present in the form of calcite in volcanic rocks.
- More importantly, blend 2 was much glassier than blend 1 (34% cf. 8%).
Glass content is the more likely reason for increased deposition.

Practical Considerations:

- Amount of ash needed constrains possible sources
 - Engineers estimate 0.1 to 1 metric tons (100-1000 kg). We must not run out of ash during experiment! Commercial quarry close to transportation, rather than geologists with shovels in the middle of nowhere, is best bet.
- Processing of ash to smaller size:
 - Note that engine compressors will pulverize ash particles into smaller sizes and different shapes (observation from previous tests by Dunn)
 - If sieving is done, minimum size of standard geologic sieve is 63 microns.
 - Or use “jet cyclone” milling process—ash dropped into opposing air blasts; particles bang against each other to self-pulverize.
 - Regardless, don’t need a precise size distribution. Looking for <100 microns with mean size that does not exceed ~60 microns.

Currently Looking At:

- Mazama Ash—pumiceous air-fall deposit from the huge eruption of Mt. Mazama that created Crater Lake ~7700 years ago.
 - Available in bulk quantities from commercial quarry in central Oregon.
 - Deposit is homogeneous rhyodacite (70% SiO₂) with ~10% of the material being mineral crystals and the rest highly vesicular rhyolitic glass (74% SiO₂).
 - Has 2-3% water incorporated into glass matrix post eruption (secondary hydration). May be enough to alter viscosity and melting temperature according to expert colleagues at Ludwig Maximilian Univ. in Munich.



Also Looking At:

- Glass Mountain Tephra—air-fall pumice from an eruption of Medicine Lake Volcano in NE California about 1000 years ago. Rhyolitic glass of 74% SiO₂. Available from a quarry. Currently being analyzed for water content.
- Cordon Caulle Ash—from 2011 eruption in Chile. Fresh, glassy, high-silica ash. Distant collection and import issues could be complications.
- Not looking at:
 - Mount St. Helens or Redoubt Volcano (thick ash deposits are not accessible).
 - Volcanoes where we have to get a permit to collect (National Parks).
 - Old cinder cones in US Southwest (not fresh, not representative of eruptions that form large ash clouds)

Suggested Analyses of Ash:

- Scanning electron microscope images of ash before and after processing.
- Relative proportions of glass and crystals, including proportions of each mineral type (plagioclase, pyroxene, etc.)
- Major elements reported as SiO_2 , Al_2O_3 , CaO , MgO , etc. of bulk sample and glass fraction (XRF analysis).
- Particle size distribution after processing (laser diffraction).
- Density of ash particles.
- Softening temperature of glass (differential scanning calorimetry).
- Melting temperature of crystals (differential scanning calorimetry).
- Water content of bulk sample (thermogravimetry).

Conclusion:

- This is the first engine test designed specifically for ingestion of volcanic ash.
- Based on a solid public-private partnership.
- While not intended to lead to rigorous regulations for certifying engine performance in ash-contaminated airspace, the experiment is a key part of a multi-pronged effort to understand ash mitigation strategies and possible health management approaches to detect ash degradation.
- And the basis for additional experiments?
- Suggestions on ash source or test design welcomed!